Adhesively bonded joints between FRP sandwich and metal

Different concepts and their strength behaviour

Markku Hentinen

Martin Hildebrand

Maunu Visuri

VTT Manufacturing Technology

VTT

TECHNICAL RESEARCH CENTRE OF FINLAND
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Abstract

This report presents several joint elements developed for joining large FRP sandwich panels to ships. Metal profiles are adhesively bonded to the panels in the prefabrication phase of the sandwich. This makes it possible to weld the FRP part directly to the metal structure in the shipyard.

Three different joint concepts were optimised and analysed taking into account the potential applications and production methods. Prototype joints of the concepts were manufactured, and the static and fatigue strength of the joints was tested under local loading conditions similar to those occurring in laterally loaded panels.

The test program of the joint concepts included welding tests, static strength tests (at room temperature, raised temperature and humidity, high temperature and after a weathering cycle), fatigue strength tests (at room temperature and after a weathering cycle), creep tests (at room temperature and raised temperature and humidity).

One joint concept was compared with a similar bolted joint alternative, which is the current practice in shipbuilding.

Preface

This work forms part of a project of the Nordic consortium for composite and sandwich technology titled "Joints of composite and sandwich constructions". The financial support from the Nordic Industrial Fund (NI) and the Technology Development Centre Finland (TEKES) is gratefully acknowledged. The authors wish to thank the industry partners of the project, Finnyards Materials Technology, Nordic Aluminium and Kværner Masa-Yards (in the first part of the project) for their contribution as experts in ship design, welding, composites and aluminium profiles, as well as for supplying the test panels and profiles for the project.

Contents

1. Introduction

Structures built of fibre-reinforced plastic (FRP) sandwich have been widely used in small high-speed craft, but FRP applications are now also introduced in components of larger ships. This is mainly due to the demand for fast vessels in which light weight is essential. For example, new HSS 1500-catamarans, built by Finnyards Oy for Stena Line, have large components manufactured of FRP sandwich.

Joining large sandwich parts to steel or aluminium structures in a reliable and economical way is a demanding task. In large components, bolting is not cost-effective as the number of bolts increases, for this slows down the manufacturing process of the joint. On the other hand, it is very difficult, even impossible, to perform adhesive bonding in a metal shipyard environment, where the conditions in terms of cleanness, temperature, and humidity form a severe obstacle for achieving adhesively bonded joints with high and even quality.

However, to overcome these problems, there is an alternative solution: prefabricated joint elements which are adhesively bonded to the sandwich panel by the FRP manufacturer and then welded to the ship structure. This allows the adhesive joint to be manufactured in a suitable environment and, on the other hand, the shipyard to weld the FRP parts to the ship in a similar manner as corresponding metal parts.

In this report, different joint concepts are evaluated, and both analysis and experimental results are presented to give an idea of the possibilities and advantages of adhesively bonded joints between FRP sandwich and metal structures.

2. Starting points for design

2.1 Potential areas of application

The most potential applications of FRP substructures can be found in areas where the benefits of light weight, free geometry and corrosion resistance are the most evident, and the disadvantages like poor fire resistance or low in-plane stiffness are not critical or the associated problems can be solved economically. Possible structures include the following [1 and 2], see also Figure 1:

− Whole sections built of fibre-reinforced plastics: Load-bearing structures of some public and residential rooms.

− Bulkheads: Interior bulkheads and B-class structures as the lightest alternative, load-bearing water-tight bulkheads as the heaviest alternative.

− Decks: Decks in public and residential rooms, car decks.

− Rails, windshelters and stairways: "Visible" structures for which aesthetics as well as ease of service is important; equipment on the upper decks, where light weight is important regarding the centre of gravity.

− Shelters and lockers: Intakes for ventilation and air-conditioning, toilets, equipment rooms.

− Masts: Radar masts.

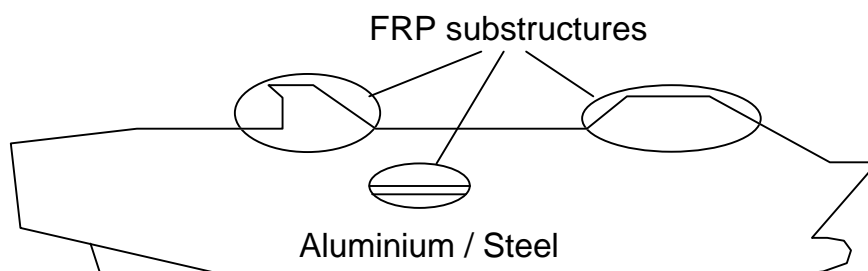− Funnels: Covering shells of funnels.

Figure 1. Potential applications for FRP sandwich structures.

2.2 Loadings

The loadings that affect the joint between the FRP substructure and metal structure, can be divided into three different types:

a) Local loads: lateral pressure and in-plane forces due to hydrostatic or hydrodynamic pressure, wind pressure, self-weight of the structure, or accelerations.

b) Global loads: Displacements and strains in the metal structure caused by still water bending moment, wave loads and slamming.

c) Stresses due to different heat expansion can be significant if the coefficients are far away from each other. Typical values for the heat expansion coefficients are [3]:

    - Stainless steel: $18 \cdot 10^{-6} \text{ K}^{-1}$

    - Aluminium: $23 \cdot 10^{-6} \text{ K}^{-1}$

    - E-glass reinforced epoxy: $10 - 12 \cdot 10^{-6} \text{ K}^{-1} (0/90°, 42 \text{ vol-}\%)$

However, the stresses in the joint due to global loads and heat expansion usually remain moderate; this is because of the relatively low in-plane stiffness of FRP laminates.

2.3 Environmental conditions

The effects of the temperature and humidity have to be considered in all abovementioned applications. Ultraviolet radiation, spray, drain or immersion in water can also be important factors that may affect the selection of the joint concept.

The temperatures typically vary between -30°C and +30°C [1]. Higher temperatures can be expected on upper decks in direct sunshine. This has to be taken into account if the difference in the thermal expansion coefficients of the materials is large. Humidity is usually high, and both spray and drain are expected on upper decks. Water-collecting cavities are thus to be avoided.

2.4 Tolerances of the adherends

Different manufacturing methods of the sandwich panel-metal profile joints require different tolerances of the components. The tolerances of the ship structures have an

effect on the required work in the assembly stage. If the inaccuracy is large and the parts are forced together, new loading components are introduced into the joint.

Thickness tolerances of the FRP sandwich panels are estimated by measuring the thickness from different panels. Table 1 presents values for sandwich panels measured by Finnyards Materials Technology and values for single skin laminates measured by VTT.

Table 1. Thickness tolerances of different FRP panels [4].

	Number of measurement points	Nominal [mm]	Max [mm]	Min [mm]	Mean [mm]
Single-skin hand/wet	12	6.0	8.1	5.6	6.3
Single-skin hand/wet	18	12.1	15.8	11.6	13.1
Balsa sandwich hand/vacuum	15	54.8	55.5	54.6	55.0
Honeycomb sandwich hand/vacuum	15	42.4	40.7	40.3	40.5
PVC sandwich pre-preg/vacuum	8	51.7	52.9	52.5	52.7
Al honeycomb hand/vacuum	15	55.5	54.2	53.8	54.0

The dimensions of the core materials are quite accurate and the differences between the maximum and minimum values mainly represent the tolerances of the laminate. The variations are often larger near the edges and bends.

Geometry restrictions of various extruded aluminium profiles are described in [5]. In the case of joining elements, the limiting factors mainly apply to mass distribution and rounding radii. Sharp edges and thin overhangs should be avoided, especially in massive profiles.

The geometry of the stainless steel profiles is restricted to the shapes that can be manufactured from flat bars or plates by bending and welding. The shape of the profile should thus be kept simple.

2.5 Heat resistance of adhesives

The concept of using 'weldable' FRP sandwich panels leads to a considerable temperature load in the joint area during the welding process in the shipyard. Hence, the

heat resistance of the adhesive materials must be suitable for the concepts, as the temperatures arising during the welding must be sustainable without damage.

Typical values of heat resistance of structural adhesives are shown in Table 2. However, it has to be noted that there are differences in heat resistance within the different adhesive types, certain products having been developed specifically for that purpose. The heat resistance of epoxy adhesives also strongly depends on the curing or post-curing temperature.

Table 2. Typical heat resistance values for different adhesive types [4].

Adhesive type	Heat resistance [°C] long time (short time without mechanical loads)
1-component polyurethane	50 - (200)
2-component polyurethane	50 - (100)
Epoxy	50 - 120 - (180)

2.6 Surface treatment and shielding

Surface treatment of the adherends and shielding of the joint have two different purposes:

− to improve adhesion between the adhesive and adherend and thus obtain higher maximum strength of the joint.

− to improve long-term strength and resistance against humidity.

It is not reasonable to manufacture adhesively bonded joints without surface treatment of the adherends [6].

Due to the presence of an adsorption layer, stainless steels usually offer higher strength than unalloyed steels in adhesively bonded joints. The rust that quickly develops on the cleaned surface of unalloyed steel is poorly fastened and leads to low strength values for the joint.

The oxide layer on aluminium surfaces has the same effect as in stainless steels. If high strength and long-term durability are needed, an artificial modified oxide layer can be formed on the surface of the metal.

The adhesive properties of fibre-reinforced plastics are governed by the matrix. The surface energy of thermoset matrices is quite high and their properties from the adhesive

bonding point of view are thus good. The surface must be roughened and cleaned before joining.

The methods of surface treatment can be divided into four main groups:

– cleaning and degreasing

– mechanical treatments

– chemical treatments

– physical treatments

Cleaning and degreasing is carried out with organic solvents. Mechanical methods include sanding, brushing and grit blasting. Various chemical methods are suitable if the number of joints is high or if mechanical treatment is otherwise uneconomic. Physical methods, like corona treatment, are mainly used for plastics that are difficult to bond adhesively, i.e. thermoplastics. [6].

The effect of different surface treatments on the shear strength of a lap joint is described in reference [6].

High temperature, humidity and loading rate affect the ageing of the adhesively bonded joints. The combined effect of these parameters is more significant than that of a single parameter, at least for epoxy-based adhesives [7].

If water or chemical solutions are able to penetrate between the adhesive and the adherend, the joint is weakened. This can happen in the following ways [6]:

1. The adhesive is applied to a humid surface.
2. Water diffuses through the cured adhesive.
3. Water penetrates into the joint along the boundary layer.
4. Water penetrates into the joint through a porous adherend.
5. Water penetrates into the joint by capillarity along possible cracks in the adhesive.

Good surface treatment is essential to avoid point 3. Shielding can affect all these points, but especially point 5.

2.7 Other requirements

Depending on the application, other required characteristics of the joint may include [1]:

a) Heat insulation. An FRP sandwich panel is an effective insulator and this can also be required from the joint.

b) Corrosion resistance. Low maintenance costs are one reason to use FRP structures in ships and the joint should be in line with this. The long-term strength of the joint also requires corrosion-resistant materials.

c) Coating. Similar coatings that are used for metal structures or sandwich panels should also be suitable for the joint.

d) Dismantling. Replacement of a damaged panel should be possible. If the metal profile is easily accessible, the joint can be dismantled by cutting the profile.

3. Evaluation and selection of concepts

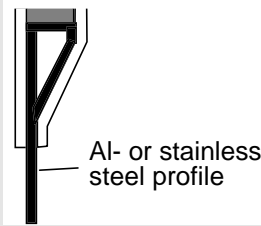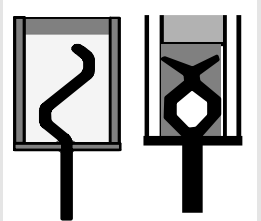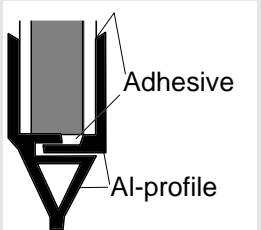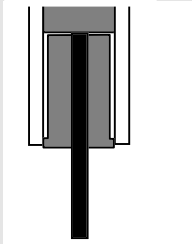There are some fundamental differences in the approaches to the joining problem:

- should the metal profile be joined to the sandwich panel simultaneously with the laminating process, or separately to a "mass produced" panel that is sawn to the right dimensions?
- should the same profile fit panels of different thicknesses?
- should bolts be used for securing the joint?
- should mechanical locking (toothing, wedges etc.) be present?
- should the profile replace some core material or should it be mounted on the outer surface of the panel?

The answers to these questions vary depending on the application. Taking also the potential applications and production methods into account, different concepts for the joint elements are developed and compared. It is assumed that the joint length per application exceeds 100 m and that the sandwich panels are constructed of glass-epoxy skins with an end-grain balsa core. Both aluminium and stainless steel are considered as construction materials for the joint elements.

3.1 Arguments for the selection

Four concepts are selected from a large number of ideas for further evaluation of the geometry, adhesive, strength and cost. These concepts are presented in Table 3.

Table 3. Summary of the joint concepts [4].

Description	Type of application	Comments
'Overlaminated' Al- or stainless steel profile 1	Laminated joints, bolted joints.	The joint must be manufactured simultaneously with the laminating process of the panel. Manufacturing the profile is quite simple. Lateral loading causes tearing stresses. The joint can be secured with bolts or rivets. Asymmetric joint.
'Flexible' stainless Al steel 2	Adhesively bonded joints, cast filling adhesive.	Manufacturing the profile is quite simple. A jig is needed for manufacturing the joint. The core must be machined from the edge of the panel. A suitable filling adhesive is crucial for success. Different profiles for steel or aluminium.
'Clevis' Adhesive Al-profile 3	Adhesively bonded joints. The two metal parts can be interlocked by welding or adhesive bonding.	Suitable for sandwich panels having different thicknesses - the tolerances can be large. No need for machining the panel edge. Draining water can affect the joint. The joint geometry suitable for carrying bending moment.
4	Adhesively bonded joints with high-density core attached to the profile.	The core must be machined from the edge of the panel. High-density core can be machined to the desired thickness and it can have borings for injection of the adhesive. Manufacturing includes many stages.

In concept 1 (overlaminated), the metal profile is joined to the sandwich panel in conjunction with the laminating process and the final dimensions of the panel must thus be known at this stage. The hollow profile replaces the core material at the edge of the panel. The geometry of the profile is quite simple and can be made of stainless steel or aluminium. The shape of the joint is asymmetric to get a smooth outer surface for the whole panel. The hollow profile can also accommodate cables etc., or it can be used as a conduit for fluids. For instance, cooling water could be utilised during the welding process.

Concept 2 (flexible) is based on a very flexible (polyurethane) adhesive filling the cavity that is machined to the core. Two versions of this concept are developed, one for a steel profile and one for an extruded aluminium profile. The adhesive with the steel profile is a one-component poyurethane, the one with the aluminium profile a two-component polyurethane elastomer.

The adjustable profile in concept 3 (clevis) makes it possible to use the same profile for panels of different thicknesses. Due to the complex shape of the profile, only extruded aluminium is practical as construction material.
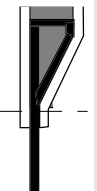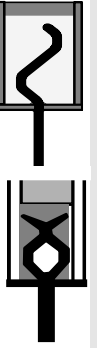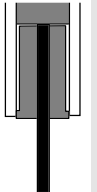
Concept 4 is suited for simple steel flat bars. However, the many stages in manufacturing the joint increase the labour cost.

3.2   Labour and material costs

Estimates for labour and material costs were collected by the project group. The amounts are approximate, but give an idea of the relative costs between the different concepts.

The costs of different manufacturing stages are presented in Table 4. It can be noticed that there is not a dominant stage in the joints, but the different positions are quite equal. The only exception is the material cost of the polyurethane adhesive in concept 2.

Table 4. Estimates for labour and material costs [4].

	Material	Profile cost	Adhesive types and costs	Production cost of the adhesively bonded joint	Assembly to the ship
1	AlSi1Mg AISI 304	70 FIM/m (4 kg/m) 150 FIM/m	primer 10 FIM/m	-	20 FIM/m
2	AISI 304 AlSi1Mg	12 FIM/kg 100 FIM/m 60 FIM/m	1-comp. PU 450 mk/m elastomer 150 FIM/m	50 FIM/m	20 FIM/m
3	AlSi1Mg	95 FIM/m (5.3 kg/m)	50 FIM/m (0.3 l/m)	20 FIM/m	20 FIM/m
4	AlSi1Mg AISI 304	43 FIM/m (2.5 kg/m) 90 FIM/m	30 FIM/m (0.2 l/m)	30 FIM/m + shielding of the underside 10 FIM/m	20 FIM/m

4. Analyses and results

4.1 Overlaminated joint concept

The analysed joints represent the edges of a laterally loaded FRP sandwich panel sized 2 × 3 m. The core material of the panels is end-grain balsa (thickness 50 mm), the face laminates being made from 0°/90° glass-epoxy prepreg.

Figure 2 shows the schematic representation of the analysed structure and the materials involved. The core is bonded to the aluminium profile with an epoxy adhesive, the thickness of the adhesive layer being 0.5 mm. The root of the aluminium profile is 7 mm thick.
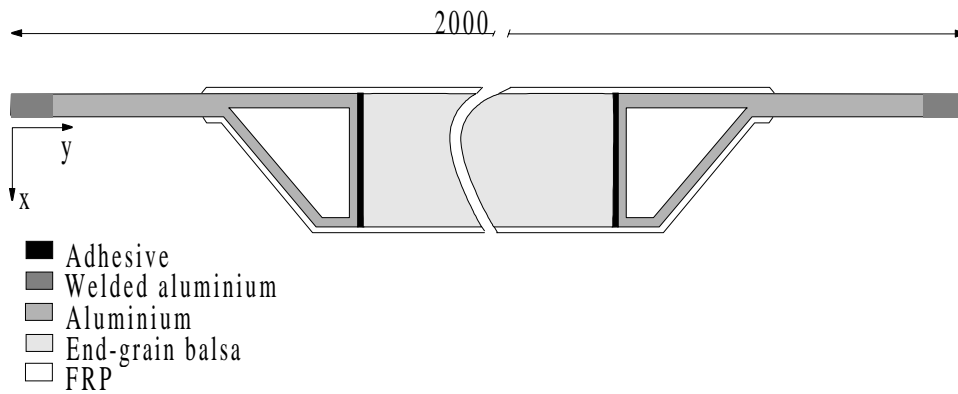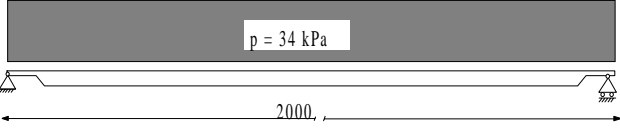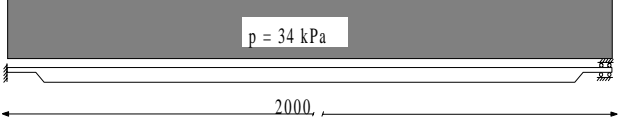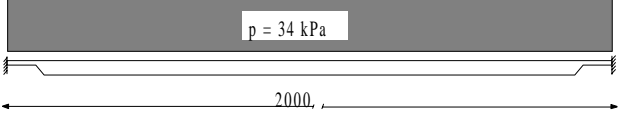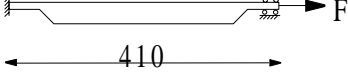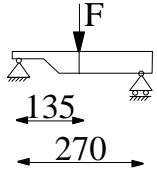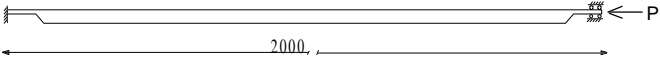
Figure 2. Schematic representation of analysed structure and materials involved. The thickness of the end-grain balsa core is 50 mm. The thickness of the FRP-faces is 2.5 mm.

Two-dimensional (plane strain) analyses of the joints were performed [8]. The analyses allow for both geometrical and material non-linearities. In the present concept, however, the most significant non-linearities are due to plasticity in the aluminium profile.

Various load cases were analysed. The first three load cases correspond to a laterally loaded panel under different boundary conditions. The loading in the joints of these cases was compared with the loading obtained in flexural and tensile tests. Table 5 shows the loads and boundary conditions of the analysed cases.

Table 5. Analysed load cases.

LOAD CASE	
1 'lateral pressure, simply supported'	p = 34 kPa 2000,
2 'lateral pressure, rotations fixed'	p = 34 kPa 2000,
3 'lateral pressure, fixed'	p = 34 kPa 2000,
4 'tensile test'	F 410
5 'flexural test'	F 135 270
6 'panel compression'	P 2000,

The analysis results for the overlaminated joint concept indicate that the critical stress concentrations in the FRP faces and the adhesive near the aluminium profile can be decreased by improving the shape of the aluminium profile. Additionally, the thickness of the end of the aluminium profile should be increased in order to avoid plastic deformations, which in turn generate high stress concentrations in the FRP faces at location B (Figure 3).
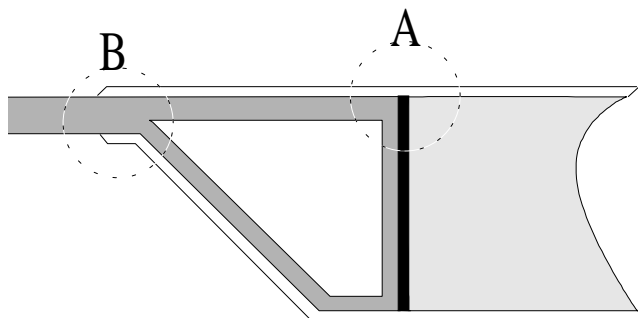
Figure 3. Critical areas of the overlaminated joint.

The flexural test (load case 5) produces a joint loading which is similar to that in the laterally loaded panel with simply supported edges. In the most critical areas of the joint, the ratio of stress levels in the FRP faces, adhesive and core is approximately the same. The joint loading generated by the tensile test is completely different to that of the laterally loaded panel.

The behaviour of the joint in in-plane compression was also studied [9]. In order to obtain a reference magnitude for the load, the stability of the corresponding panel under in-plane compression is analysed under different boundary conditions. The results of the analysis show that the stress distribution in the joint under compressive in-plane loads is similar to the one resulting from transverse pressure load of the panel.

4.2 Flexible joint concept

The adhesive used in the flexible joint concept with the steel profile was a one-component polyurethane adhesive with a break elongation of 300 %. The analysis of such flexible materials requires rather specific solution techniques, which are used for the analysis of rubber structures. To model the measured stress-strain behaviour of the adhesive, a Mooney-Rivlin material model was used (Figure 4) [4].
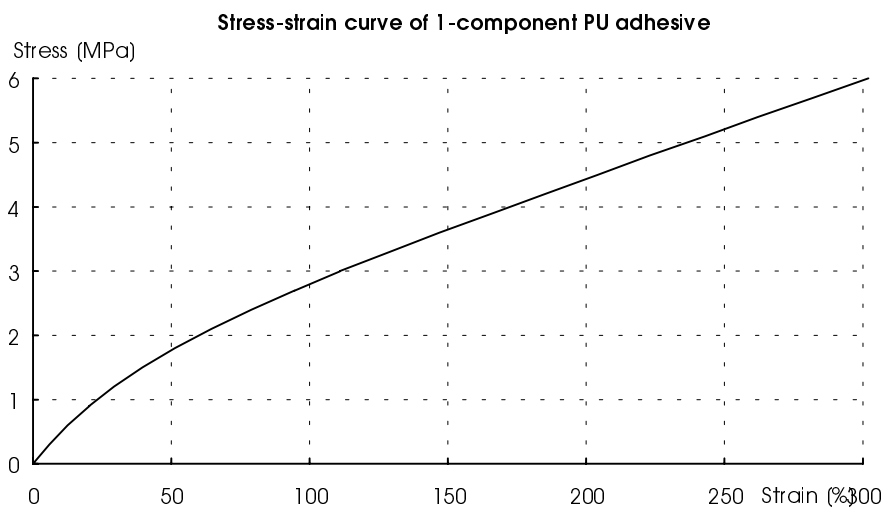
Figure 4. Stress-strain behaviour of the 1-component PU-adhesive.

The geometry of the joint area is shown in Figure 5.

Steel   FRP   Balsa   Adhesive
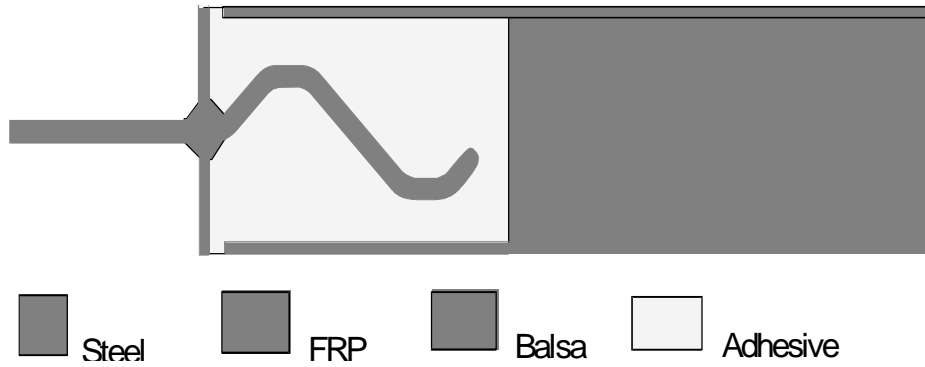
Figure 5. Geometry of the flexible joint with stainless steel profile.

The behaviour of this joint was analysed in a panel under lateral load as well as in the tensile and flexural test. The boundary conditions of the panel were rotations fixed and in-plane displacements free.

The analysis results indicate that this concept offers adequate strength compared with the other concepts. Compared with the overlaminated concept, the joint is more flexible: in terms of mid-panel deflection, the stiffness of the panel decreases by up to 14% which, however, is not dramatic. One of the potential benefits of such a concept is the vibration damping capability of the joint.

The critical areas of the joint in a laterally loaded panel are shown in Figure 6. The highest strains in the adhesive occur at locations A, near the end of the FRP faces. The most critical area of the FRP faces is at locations B, due to the local bending introduced by the difference in stiffness between core and adhesive. The most critical part of the core is in the middle near the steel profile where the transverse tensile stresses are the highest. The low transverse tensile strength of the end-grain balsa core is the weak link in this concept. However, with other core materials (PVC foam) this weakness does not occur.
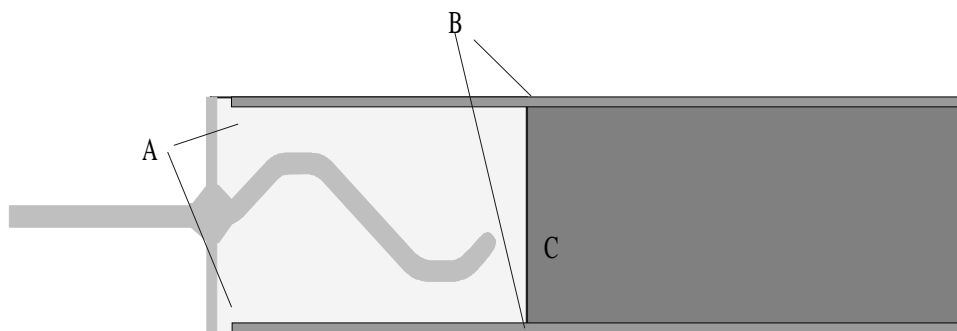
Figure 6. Critical areas of the flexible joint (with steel profile) in a laterally loaded panel.

5. Experiments and results

5.1 Welding tests

Welding tests to estimate the maximum temperature in the joint during the welding process were carried out by Kværner Masa-Yards. Preliminary values for butt welds in different specimens were measured with temperature-sensitive chalk. More detailed measurements with temperature gauges were carried out for test panels [10] with the overlaminated joint.

The length of the panels in the welding tests was 500 mm (panels for tensile test specimens) and 1 000 - 1 700 mm (panels for bending test specimens). The eight temperature gauges were installed halfway of each panel as shown in Figure 7.
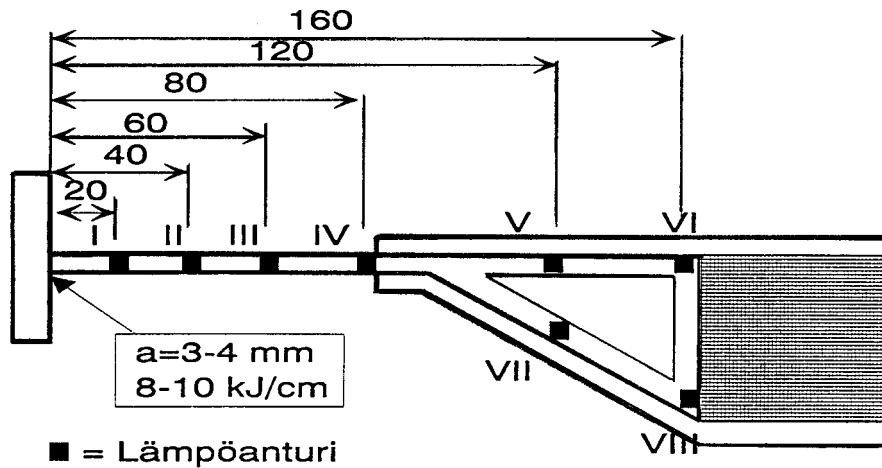
Figure 7. Location of the temperature gauges in the cross-section of the joint. The temperature gauges are indicated by the symbol ■ [10].

Fillet welding was chosen to represent the normal joint type in relevant structures. T-shaped pieces were manufactured and welded to the profiles. The second side of the joint was welded immediately after the first one. The temperature was registered at the eight measuring points, at an interval of 10 seconds. This was continued until the temperature at each measuring point was under 40°C.

5.1.1 Aluminium profiles

In the case of aluminium profiles, the material of the T-shaped pieces was 7-mm AlSi1Mg and the width of the pieces varied from 50 to 250 mm. According to the results, heat propagates quickly over the whole profile (see Figure 8). Maximum temperature depends strongly on the heat conduction away from the critical areas. This

is strongly affected by the width of the additional T-piece: the maximum temperature at point 4 decreases from 160°C to about 85°C as the width increases from 50 to 250 mm. As a conclusion, the adhesive joint is not damaged if the metal structure is massive enough to assure heat conduction away from the joint. The distance between the weld and the adhesive joint can even be decreased in such cases.
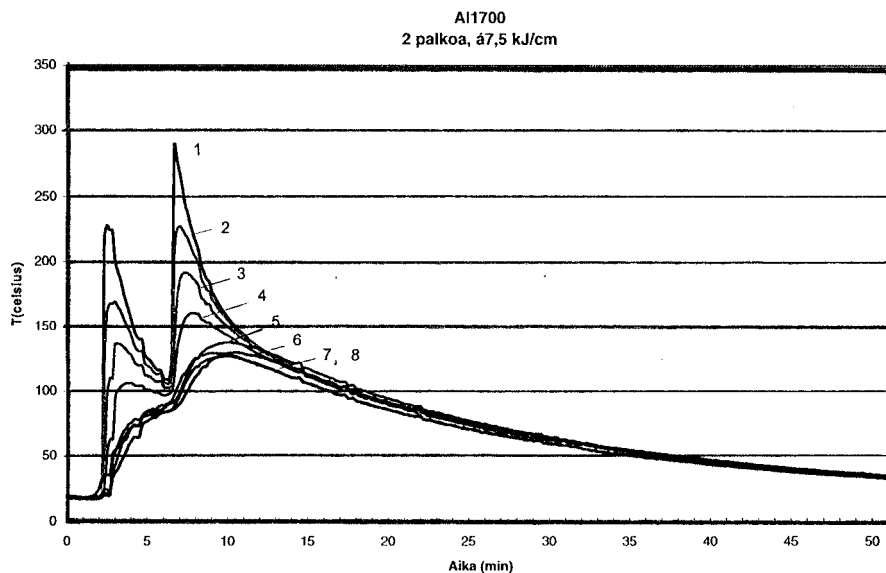
Figure 8. Temperature at 8 measuring points as a function of time during the welding test performed for the aluminum profile. Width of the additional piece is 50 mm. [10]

5.1.2   Stainless steel profiles

According to the results, 80 mm is a sufficient distance between the weld and the adhesive, as the temperature at point 4 does not exceed ~80°C when the width of the additional T-piece is 50 mm. The maximum temperature decreases to ~65 °C if the width of the piece is increased to a more realistic 200 mm.

The maximum allowable temperature is difficult to determine exactly, as adhesive manufacturers rarely supply information of the short term heat resistance of their products. However, the temperatures in the overlaminated joint concept seem to be sufficiently low at the laminate edge, if the structure below the joint element is massive enough.

The additional T-shaped pieces used with stainless steel profiles were of 6-mm carbon steel, and the width of the pieces varied from 50 to 200 mm. Because of the relatively low heat conductivity of austenitic stainless steels, it takes about 30 minutes until the temperature levels out in the profile, see Figure 9.
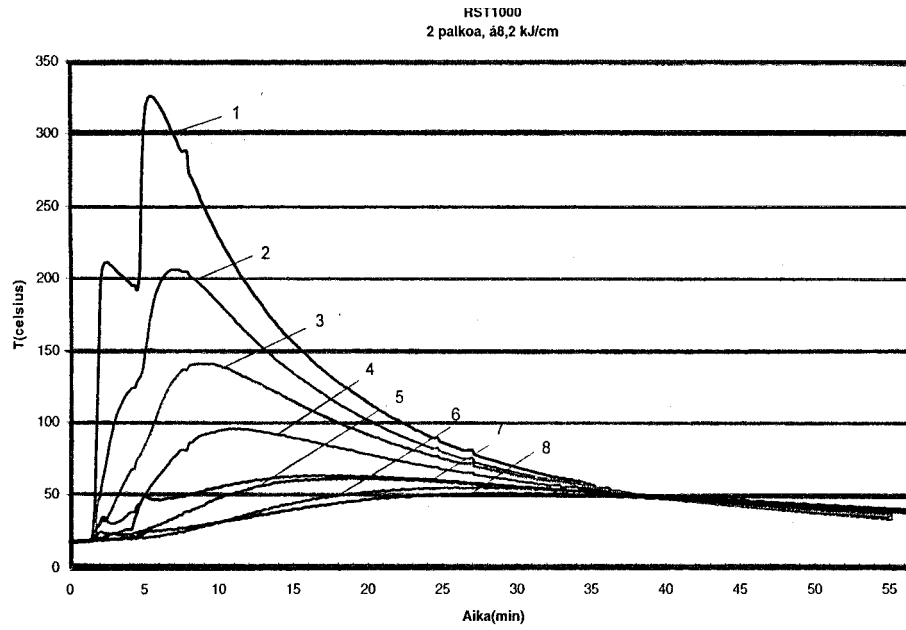
Figure 9. Temperature at 8 measuring points as a function of time during the welding test performed for the stainless steel profile. Width of the additional piece is 50 mm. [10]

5.2 Static strength tests

Tensile and three-point bending tests were performed both with the aluminium-FRP-sandwich and stainless steel-FRP-sandwich joints for the overlaminated, clevis and flexible joint concepts [11, 12]. The static tests were performed at loading rates of 2 and 4 mm/min in the tensile and flexural tests respectively.

Two different surface treatments were used: degreasing-sanding-degreasing and degreasing-grit blasting-silane primer application.

The specimens were tested under different conditions. A part of the test specimens were tested after undergoing a weathering cycle. Some of the specimens were tested in room conditions, some at elevated temperature and humidity (40°C/85% RH) and some at high temperatures (200°C).

The test matrix is shown in Table 6.

Table 6. Performed tests and number of specimens tested in each case.

Joint type	Tensile test	Number of specimens	Flexural test	Number of specimens
Al	Dry + RT	5[a]	Dry + RT	5[a] + 5[b]
			40°C/85%	5[b]
			Weathering + RT	5[b]
			200°C	5[b]
Steel	Dry + RT	5[a]	Dry + RT	5[a]
Al	Dry + RT	5[a]	Dry + RT	5[a] + 5[b]
			40°C/85%	5[b]
			Weathering + RT	5[b]
			200°C	5[b]
Steel	Dry + RT	5[a]	Dry + RT	5[a]
Al			Dry + RT	5[b]
			40°C/85%	5[b]
			Weathering + RT	5[b]

RT	Room temperature
40°C/85%	Tested in temperature of 40°C and in relative humidity of 85%
Weathering	Specimens have undergone a separate weathering cycle before testing
200°C	Specimens tested at 200°C
[a]	Surface treatment without primer
[b]	Surface treatment with primer

5.2.1 Weathering cycle

The weathering cycle was performed according to the standard ASTM D 1183 - 70: "Standard Test Methods for Resistance of Adhesives to Cyclic Laboratory Ageing Conditions". The standard (exterior/marine use) and the performed cycles are shown in Table 7.

Table 7. The standard method and performed cycles in the weathering tests. The first performed cycle was applied to the overlaminated and clevis joints. The second cycle was applied to the flexible joints.

Standard ASTM D 1183 - 70: "Standard Test Methods for Resistance of Adhesives to Cyclic Laboratory Ageing Conditions"			Performed first cycle		Performed second cycle	
Period [h]	Temperature [°C]	Relative humidity [%]	Period [h]	Temperature [°C]	Period [h]	Temperature [°C]
48	71 ± 3	< 10	48	71	48	71
48	23 ± 1.1	Immersed in substitute ocean water	48	23	54	23
8	-57 ± 3	approximately 100	16[1]	-50 .. -58°C	9[1]	-50 .. -60°C
64	23 ± 1.1	Immersed in substitute ocean water	65	23	64	23
1) Test specimens were within the standard regime for 8 hours The relative humidity in both test series was in the regime given by the standard						

5.2.2 40°C/85% RH conditions

The specimens to be tested in the temperature of 40°C and relative humidity of 85% were first kept from 7 to 8 days in these conditions so that the specimens were fully exposed. The tests were carried out in a special "box" which was designed and built to keep these conditions steady during the tests. During the static tests, on an average, the air temperature in the box decreased to 33 - 36°C in 6 - 15 minutes test time. This can be considered acceptable, as the temperature of the test specimens drops more slowly than that of the surrounding air.

5.2.3 High temperature (200°C)

In many marine structures, fire safety must be taken into account in the dimensioning and selection of materials. In the present case, the heat conducted to the joint via the metal profile was considered critical. Therefore, static strength tests were carried out for specimens after heating them to a temperature of 200°C in an oven.

5.2.4 Tensile test results

The tensile tests were performed on specimens of the overlaminated joint concept (both aluminium-FRP and stainless steel-FRP joints, the clevis joint (aluminium profile) and

the flexible joint concept (stainless steel-FRP). The test resuls of the clevis and flexible joint concepts are evaluated more in detail than those of the overlaminated joint concept.

Figure 10 shows the sizes of the tensile test specimens.

Figure 10. Specimen sizes (overlaminated joint) in the tensile test. The specimen dimensions for the clevis and flexible joints are similar. [11]

The average test results are shown in Table 8. In some cases, the standard deviation was high. This must be carefully considered when interpreting the average value results.

Table 8. Average tensile test results [11, 12].

	Strength at first failure [N/mm]	Maximum strength [N/mm]	Maximum deflection [mm]	Stiffness [(N/mm)/mm]	Toughness [(N/mm)*mm]
Al [a]	ne	537	ne	ne	ne
Steel [a]	ne	296	ne	ne	ne
Al [a]	74	413	13.5	70	5635
Steel [a]	62	199	45.0	17	10483
[a] surface treatment without primer ne = not evaluated					
[b] surface treatment with primer					

In the overlaminated joint, the failure started in both cases (aluminium and steel) from location A as a debonding between the FRP face and the metal profile. The FRP face debonded from A to location C (see Figure 7), resulting in an instant loss of stiffness.

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The critical areas of the clevis joint are shown in Figure 11. The first failure occurred at the location A (Figure 4), where the joint between the two aluminium profiles debonded. The second and final failure occurred at location(s) B and/or C, where the FRP laminate debonded from the aluminium profile (B) or the aluminium profile broke apart (C). In addition to tensile force, test specimens were subjected to a bending moment due to asymmetry of the aluminium profile assembly
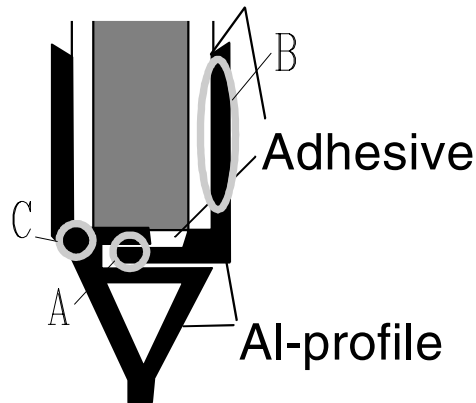
Figure 11. Critical areas of the clevis joint.

The critical areas of the flexible joint with steel profile are shown in Figure 12. Debonding of the polyurethane adhesive from the steel profile started at the location A, where a preliminary gap existed before the tests. The first failure is a transverse tensile failure in the balsa core (B). After this the flexibility of the polyurethane adhesive allowed deflections of 40 - 60 mm before final failure. The final failure occurred when one of the two face laminates debonded from the polyurethane adhesive (C).

Figure 12. Critical areas of the flexible joint.

The maximum tensile strength of the clevis joint is approximately two times as high as that of the flexible joint. The overlaminated joint has a 2.7 (aluminium profile) or 1.5 (steel profile) times higher maximum s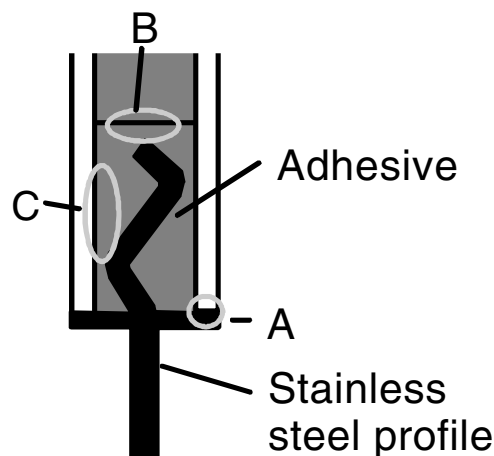trength than the flexible joint. The first failure levels of clevis and flexible joints are approximately equal. The deflection level in the flexible joint is over three times as high as in the clevis joint. Considering the construction of the joint types, the results are not unexpected.

The differences in stiffness (force per width divided by deflection) are large. The clevis joint is approximately 4 times as stiff as the flexible joint. The opposite is true for the toughness (amount of absorbed energy, maximum force per width × deflection), where the flexible joint is 2 times as tough as the clevis joint.

5.2.5 Flexural test results

3-point flexural tests were performed with the overlaminated (both aluminium and stainless steel profiles), clevis (aluminium profile) and flexible (both aluminium and stainless steel profiles) joint concepts. As presented in Chapter 4.1, the geometry of the bending test specimens was chosen so that the stress distribution in the joint was similar to the laterally loaded panel. Because the required loading condition is a combination of bending and shear forces, the results are presented as force per width.

Figure 13 shows the sizes of the test specimens.
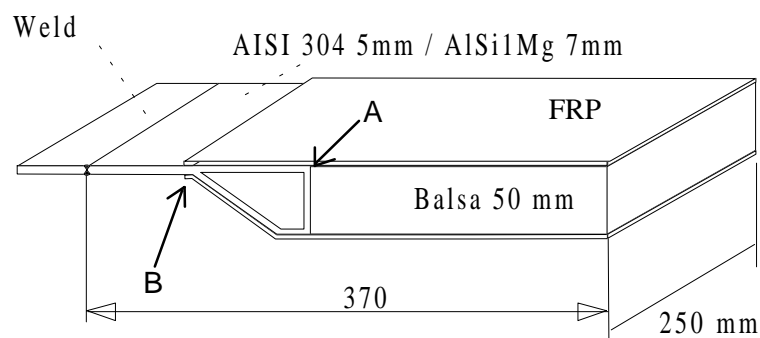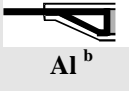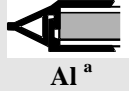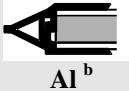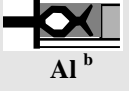

Figure 13. Specimen sizes (overlaminated joint concept) for the 3-point flexural test. The specimen dimensions for the clevis and flexible joint concepts are similar. [11]

The average test results are shown in Table 9.

Table 9. Average static test results [11, 12].

Joint type	Condition	Strength at first failure [N/mm]	Maximum strength [N/mm]	Deflection at maximum strength [mm]	Stiffness [N/mm/mm]	Toughness [N/mm*mm]
Al [a]	Dry + RT	48	121	4.7	28.2	569
Al [b]	Dry + RT	123	142	6.1	27.4	889
	Weathering + RT	108	132	6.6	22.5	893
	40°C/85%	112	127	9.6	21.5	1225
	200°C	-	1	0.5	-	0.5
Steel [a]	Dry + RT	98	99	5.0	33.0	495
Al [a]	Dry + RT	-	127	1.9	51.0	282
Al [b]	Dry + RT	-	149	2.2	48.1	334
	Weathering + RT	-	146	3.9	37.6	562
	40°C/85%	-	164	3.5	38.5	567
	200°C	-	5	1.0	-	5.0
Steel [a]	Dry + RT	18	54	18.7	7.0	1009
Al [b]	Dry + RT	44	106	17.5	11.9	1853
	Weathering + RT	44	97	15.9	10.4	1542
	40°C/85%	44	97	17.0	8.6	1674

In the overlaminated joint concept, the first failure occurred at location B (see Figure 10). The lower face debonded from the profile over a width of around 30 - 40 mm from the laminate end. However, the debonded area did not grow further during the tests. Ultimate failure occurred at location A (see Figure 10), the failure type being delamination between the FRP face and core and subsequent core shear failure. The failure mechanism was similar in the aluminium and steel-FRP sandwich joints.

In the flexural tests the same effects as in the tensile tests are present, i.e. due to the flexibility of the polyurethane adhesive, the flexible specimens have higher deflections and smaller maximum force per width than the clevis joint specimens. The clevis joint test specimens broke due to core shear failure outside the joint without any indication of first failure in the joint area.

The differences in stiffness (force per width divided by deflection) were large. The clevis joint was approximately 7 times as stiff as the flexible joint. The opposite is true for the toughness (amount of absorbed energy, maximum force per width × deflection), where the flexible joint was 4 times as tough as the clevis joint. The overlaminated joints lies in terms of stiffness and toughness between the clevis and the flexible joint.

The first failure value for the flexible joint was based on visual observation. In the clevis joint, there was no indication of first failure before the final failure.

The effect of the different surface treatments on the strength is considerable. In the overlaminated joint with aluminium profile, the silane primer led to a 2.5 times higher strength at first failure and to an increase of 17% in maximum strength. In the clevis joint, the increase of maximum strength due to the silane treatment was also 17%.

An interesting observation is that the effect of specimen conditioning and testing conditions on the joint strength is only moderate: the decrease in maximum strength after weathering is below 10% for the overlaminated, clevis and flexible joint with aluminium profiles. The 40°C/85% RH conditions lead to a decrease in maximum strength of 12% in the overlaminated joint. In the clevis joint, the strength is even increased by 10%, but it must be kept in mind that the failure occurs in the balsa core material outside the joint area. In the flexible joint, the decrease in maximum strength due to the higher temperature and humidity is 8%.

After the exposure to high temperatures (200°C), most of the panels were clearly damaged (faces debonded from core). As expected, the strength values were very low (about 1 - 5 N/mm) and the strength of the adhesive joint could not be measured. More suitable test methods should be developed to simulate the heat conduction.

5.3 Fatigue tests

Aluminium structures are known to have relatively poor fatigue strength as compared to FRP laminates. The fatigue strength of the joint concepts was examined with fatigue tests for weathered and dry specimens. The test matrix is shown in Table 10.

Table 10. Performed fatigue tests and number of specimens tested in each case.

Joint type	Conditions	Loading	Number of specimens
Al [b]	Weathering + RT	80%, R = 0.1	5
	Weathering + RT	70%, R = 0.1	5
	Weathering + RT	60%, R = 0.1	5
	Dry + RT	80%, R = 0.1	5
Al [b]	Weathering + RT	90%, R = 0.1	5
	Weathering + RT	80%, R = 0.1	5
	Weathering + RT	70%, R = 0.1	1
	Dry + RT	80%, R = 0.1	4
Al [b]	Weathering + RT	80%, R = 0.1	1

RT	Room temperature
XX%	XX% level of the static strength. In the case of the flexible joint, the 80% level was taken from the approximated first-failure level.
Weathering	Specimens have undergone a separate weathering cycle before testing
Dry	No weathering before testing
[b]	Surface treatment with primer

All fatigue tests were performed with the ratio one to ten (R = 0.1) between minimum and maximum force. The frequency was 1 Hz for the overlaminated and flexible joint type, and 2 Hz for the clevis joint. Maximum force levels between 60% and 90% of the equivalent average static strengths were used for the overlaminated and clevis joint types. For the flexible joint type, 80% of the static first failure strength was selected. This was due to the larger deflections and the earlier first failure values of that joint type. The test results are shown in Table 11.

Table 11. Fatigue test results, R = 0.1. The number of cycles at first failure (N_{ff}) has been approximated from the cycles-deflection curve at a point where deflection starts to increase.

Joint type	Conditions	Load	N_{mean}	N_{ffmean}	N_{min}	N_{max}	Failure type	
	Dry / RT	80%	18775	553	17600	19400	laminate	1
							aluminium	4
	Weathering / RT	80%	7450	671	350	11000	balsa	1
							aluminium	4
	Weathering / RT	70%	18700	633	2050	28800	balsa	2
							aluminium	3
	Weathering / RT	60%	50100	575	50100	81550	laminate	1
							aluminium	4
	Dry / RT	80%	160750		26800	347600	balsa + cracks in aluminium	
	Weathering / RT	90%	3543		15	10750	balsa + cracks in aluminium	
	Weathering / RT	80%	142210		200	360750	balsa + cracks in aluminium	
	Weathering / RT	70%	>4300000		>4300000	>4300000	balsa	
	Weathering / RT	80%	>1035951					

N_{mean}	average number of cycles to failure
N_{ffmean}	average number of cycles to first failure
N_{min}	lowest number of cycles to failure ("weakest specimen")
N_{max}	highest number of cycles to failure ("strongest specimen")
Failure type	balsa = shear failure in the core, aluminium = failure in the extruded profile, laminate = flexural failure in face laminate

The number of cycles at first failure was possible to observe from the cycles-deflection curve for the overlaminated joint only. The other curves did not show such increase in deflection.

The results for the overlaminated joint concept are shown in Figure 14. Compared with the static strength values, the fatigue strength can be considered high. The failures occurred in the aluminium profile and balsa core (see Figure 15) or, in two specimens, in the laminate.

Overlaminated joint, static and fatigue tests of the weathered specimens

Figure 14. Fatigue test results for the overlaminated joints, R = 0.1.

Figure 15. Typical failures during the fatigue tests for the overlaminated joints.

The results for the clevis joint concept are shown in Figure 16. Keeping in mind that the highest load level is very near of the equivalent average static strength, the fatigue strength can be considered very high. The failures occurred in the balsa core outside the aluminium profile and, additionally, cracks appeared in the aluminium profile.

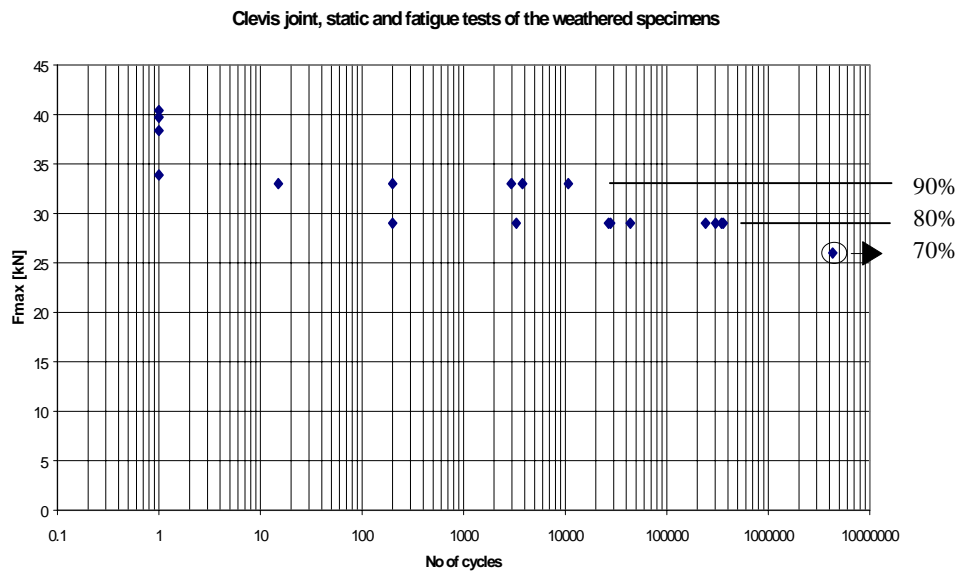**Clevis joint, static and fatigue tests of the weathered specimens**

Figure 16. Fatigue test results for the clevis joints, R = 0.1. The specimen tested at the lowest load level (26 kN) did not break after 4 300 000 cycles.

Only one flexible joint specimen was tested, and even that did not break after 1 035 951 cycles. Had the maximum load level been raised, the static first failure strength would have been exceeded. This was not considered relevant, and no other specimens were tested in this project. However, based on the result of the one specimen, the fatigue strength seems promising.

5.4 Creep tests

The flexible joint type was considered to be the only one of the three concepts that could be creep-critical. Therefore, a test series using a high load-level was carried out on dry (not weathered) specimens both in room temperature and in elevated temperature and humidity (45°C/80% RH) conditions.

The width of the specimens was 50 mm and the corresponding static first failure load was 2.75 kN. The results are shown in Figures 17 and 18.
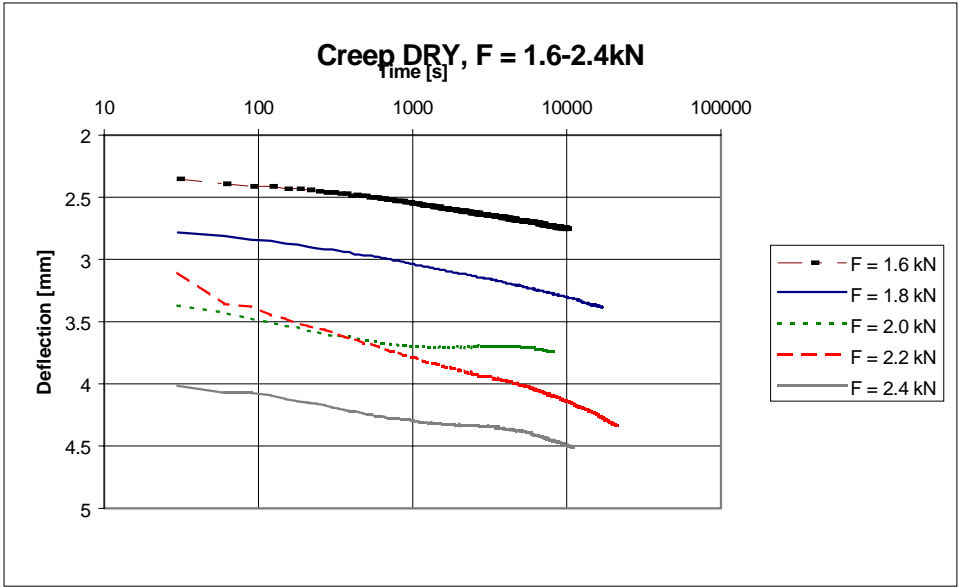
Figure 17. Creep test results for dry (not weathered) flexible joints in room temperature.

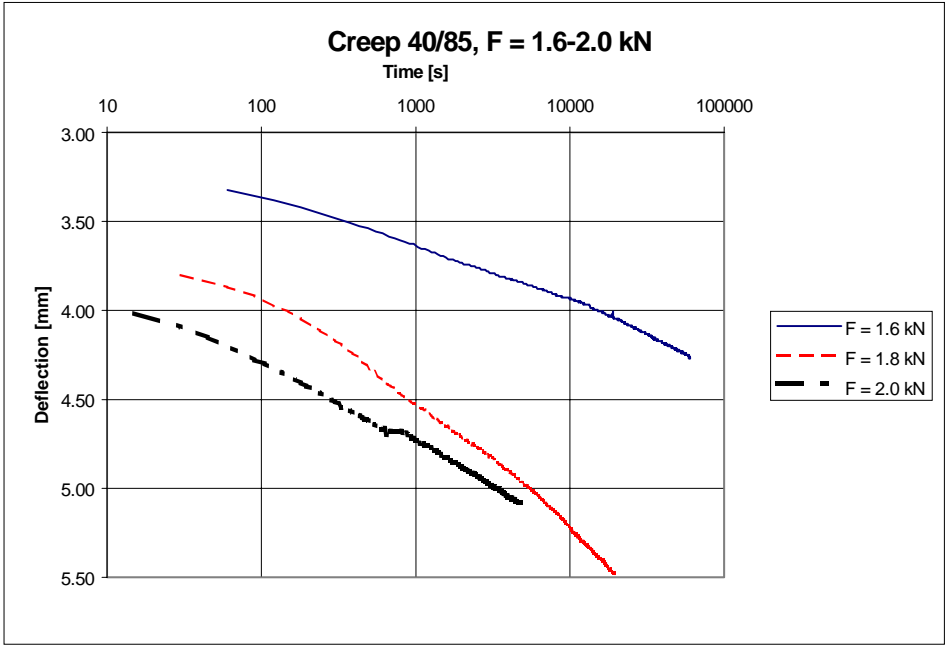*Figure 18. Creep test results for flexible joints (not weathered) in raised temperature (40 °C) and humidity (85 %).*

According to the results, in room temperature the creep is quite small even with high load levels (about 90% of the static first failure load). The raised temperature and humidity do have a clear effect on the creep behaviour of the joints. This is an area for further research.

6. Correlation between the experiments and the analysis

6.1 Overlaminated joint concept

The correlation of the bending deflection between the flexural tests and the analysis is good [4]. However, after the first failure, the stiffness of the joint is slightly reduced. This effect is not modelled in the analysis (Figure 19).
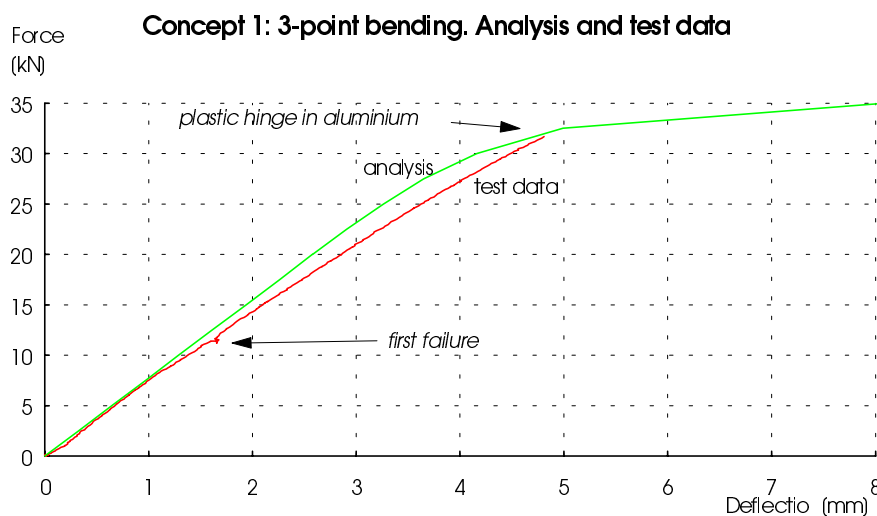

Figure 19. Correlation between analysis and flexural test results of the overlaminated aluminium-FRP-sandwich joint.

The force at which the ultimate failure of the specimen occurs lies at the same level as where the analysis results suggest the beginning of a plastic hinge in the aluminium profile (location B, Figure 3). Hence, the ultimate joint strength is at a level above which it cannot be increased without changing the thickness of the aluminium-profile root.

6.2 Flexible joint concept

The correlation between experiments and analysis is shown in Figures 20 and 21 for the flexural and tensile test [4].

It appears that the local geometry at the ends of the FRP faces has a great influence on the bending stiffness of the joint. Unfortunately, it is difficult to control this area exactly

in practice and, consequently, variations in stiffness are also present in the tested specimens. The test data curves shown in Figures 20 and 21 represent the two specimens with lowest and highest stiffness respectively.

The analysis of the flexural test was performed with different local geometries. The model was analysed using three different sizes of the gap between the end of the FRP faces and the steel profile. In some of the models, the gap was filled with adhesive. In some of the models, the contact between outer FRP face and steel profile was modelled with contact elements. If contact occurs, the stiffness of the joint increases, and the stresses in the adhesive are redistributed resulting in higher strains in the adhesive near the inner face.
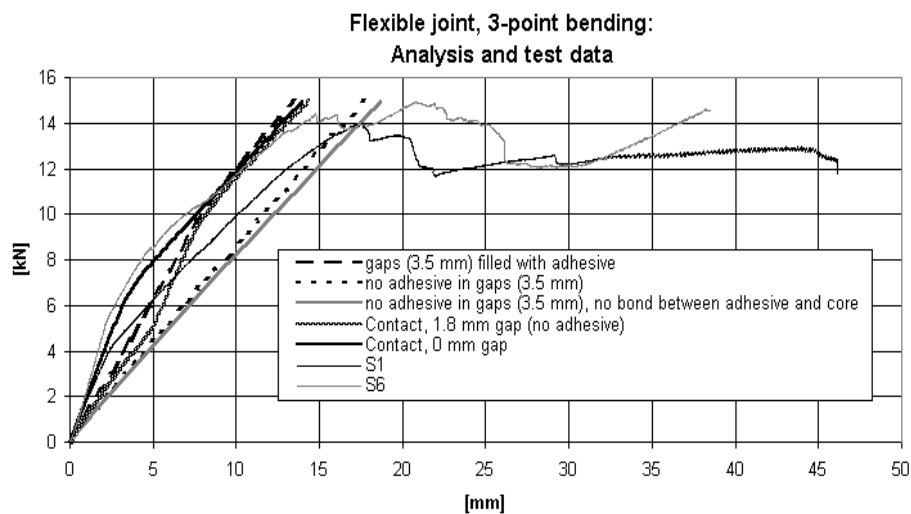

Figure 20. Correlation between experiments and analysis of the flexible joint with stainless steel profile in the flexural test. Test data shown for the specimens with highest (S6) and lowest (S1) stiffness.

The correlation between experiments and analysis in the tensile test is shown in Figure 14. Transverse tensile failure occurred in the core material already at a low load level. Therefore, the analyses were made with different models, with and without bond between adhesive and core. Due to transverse tensile failure in the core, the stresses in the adhesive were redistributed, which resulted in higher stresses near the ends of the FRP faces.

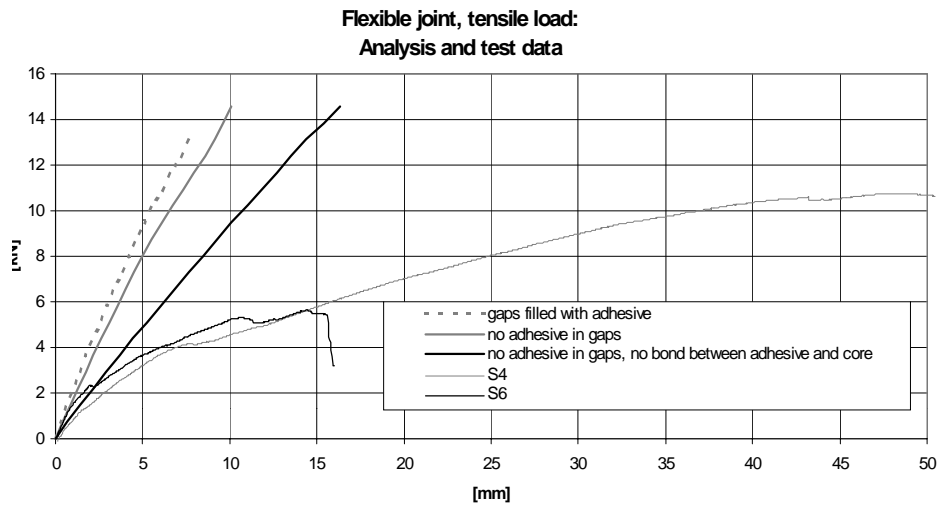*Figure 21. Correlation between analysis and tensile test results. Test data for the specimens with highest (S6) and lowest stiffness (S4).*

Below the level of first failure, the calculated displacements agree well with the measured ones. Taking into account and modelling the consequences of first failure (transverse tensile failure of the core material), the behaviour of the joint can be analysed slightly further.

7. Comparison of the overlaminated joint with a similar bolted joint type

The overlaminated joint concept can be compared [4] with a similar joint type where the FRP sandwich is directly bolted to the metal structure (Figure 22). The bolted joint also uses an adhesive in order to achieve water tightness.
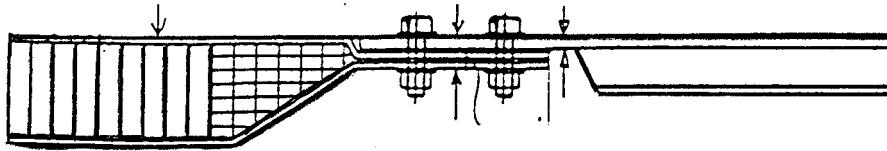

Figure 22. Geometry of the comparable bolted joint type [13].

This bolted joint type is common practice in shipbuilding today, but it is known to be rather cost-intensive due to the large amount of man-hours involved in the bolting. The strength properties of this bolted joint type have been measured earlier [13] and, due to the similar test configuration and specimen geometry, the measured strength values in tension and flexure can be compared with the overlaminated concept. The comparison is the most interesting regarding the amount of labour involved in both joint types (Table 12). The manufacturing costs of the bolted joint are known from joints used in current structures, whereas the manufacturing cost of the adhesively bonded joint have been determined during the manufacture of the test specimens [14].

Table 12. Comparison of both strength and manufacturing costs of the overlaminated joint concept and a similar bolted joint type.

		overlaminated joint concept	bolted - bonded
Strength:	Flexural test - force per width at first failure	48 N/mm	18 N/mm
	Flexural test - force per width at break	121 N/mm	18 N/mm
	Tensile test - force per width at break	537 N/mm	507 N/mm
Manufacturing costs:			
	Panel edge preparation	100%	100%
	Joining to ship	100%	220%

The test specimens of the bolted joints differed in two aspects from the adhesively bonded joint. Firstly, the core material in the flexural test specimens was aluminium honeycomb, with the exception of the sandwich where end-grain balsa was used. However, this is not considered to have an influence on the flexural strength, because the shear stiffness of aluminium honeycomb and end-grain balsa is similar. The bolted specimens failed at the panel edge, where the core material was balsa. Secondly, in the tensile test specimens of the bolted joint, the core thickness was only 25 mm, the core material being end-grain balsa.

8. Conclusions

Four joint concepts were developed for joining large FRP sandwich parts to metal structures especially in ship applications. The concepts were based on a pressure loaded 2×3 m sandwich panel representing a typical FRP structure on upper decks.

Two of the joint concepts were analysed with non-linear FE-methods. The analyses show that the chosen flexural test configuration produces in the joint a stress distribution similar to that of a pressure loaded sandwich panel.

Based on the test program, the following conclusions are suggested:

- All four concepts are technically feasible. Excessive temperatures during welding can be avoided by locating the adhesive bond at a reasonable distance from the weld.

- The static strength of the joints is adequate compared with the strength of the sandwich panel.

- The fatigue strength is high as compared with the strength of the FRP sandwich panel and the metal joint elements.

- The correlation between the analyses and the experiments (flexural test) is good up to the point of first failure for both overlaminated and flexible joints.

- When comparing the overlaminated joint concept with a similar bolted joint alternative, which is the current practice in shipbuilding, the numerical analyses and experiments confirm that the static strength of the overlaminated joint is higher than that of the bolted joint. Additionally, the adhesively bonded concept is clearly more cost efficient, reducing the manufacturing costs during the joining to the ship by as much as 50%.

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